

# Midterm Review

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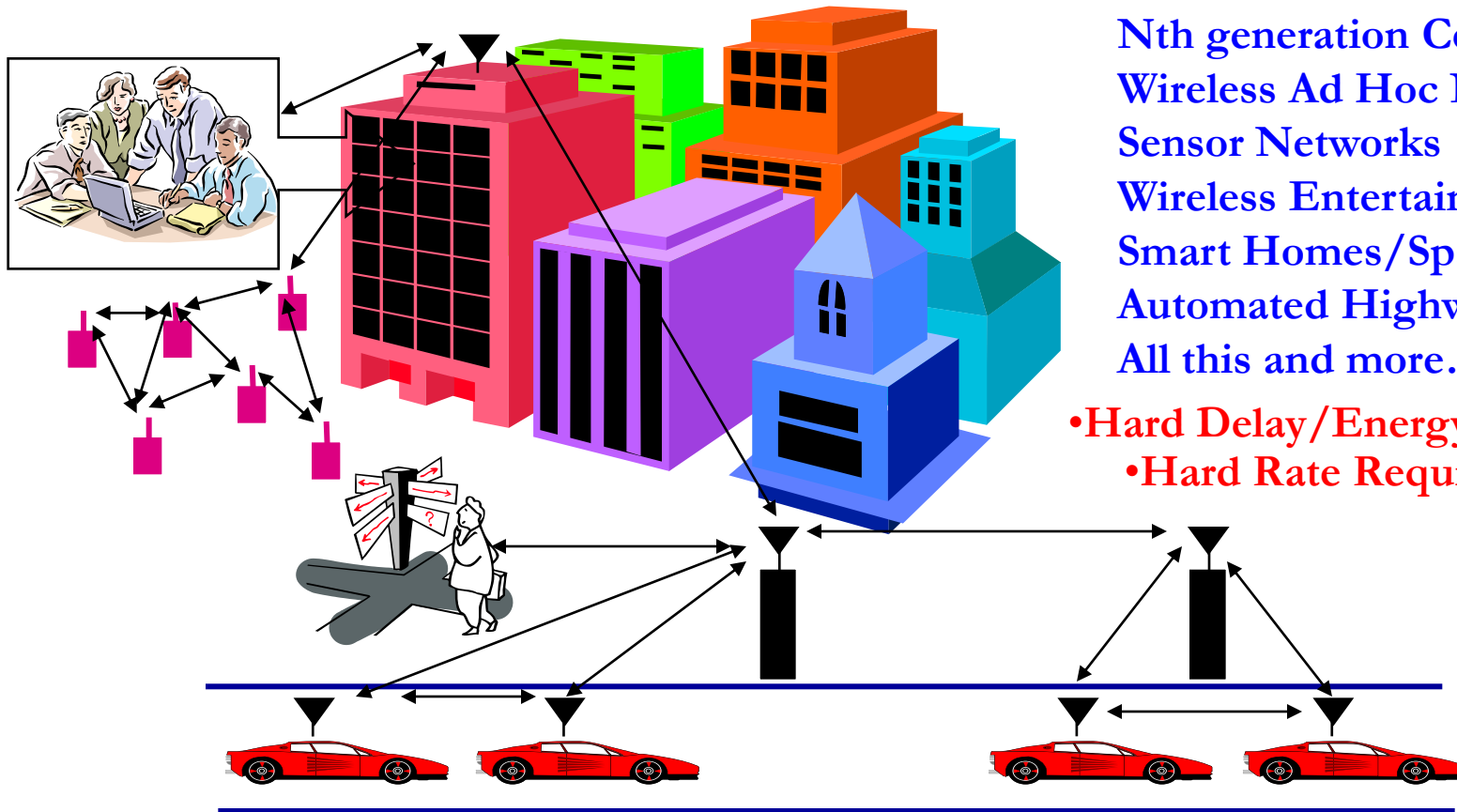
- Overview of Wireless Systems
- Signal Propagation and Channel Models
- Modulation and Performance Metrics
- Impact of Channel on Performance
- Fundamental Capacity Limits
- Diversity Techniques

# Future Wireless Networks

## *Ubiquitous Communication Among People and Devices*

Wireless Internet access  
Nth generation Cellular  
Wireless Ad Hoc Networks  
Sensor Networks  
Wireless Entertainment  
Smart Homes/Spaces  
Automated Highways  
All this and more...

- Hard Delay/Energy Constraints
- Hard Rate Requirements



# Design Challenges

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- **Wireless channels are a difficult and capacity-limited broadcast communications medium**
- **Traffic patterns, user locations, and network conditions are constantly changing**
- **Applications are heterogeneous with hard constraints that must be met by the network**
- **Energy, delay, and rate constraints change design principles across all layers of the protocol stack**

# Current Wireless Systems

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- Cellular Systems
- Wireless LANs
- Wimax
- Satellite Systems
- Paging Systems
- Bluetooth
- Zigbee radios

# Signal Propagation

- Path Loss

- Free space, 2-path,...
- Simplified model

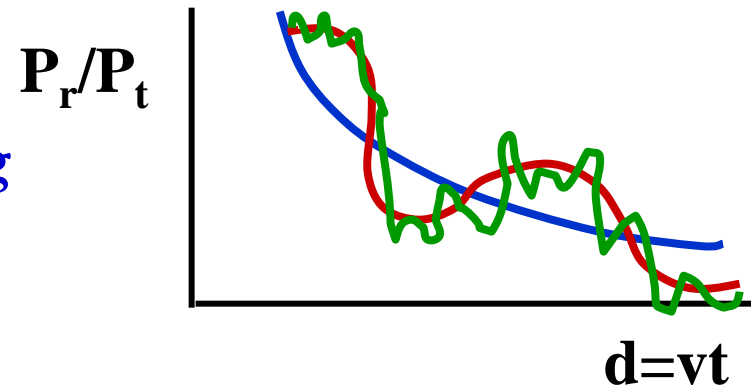
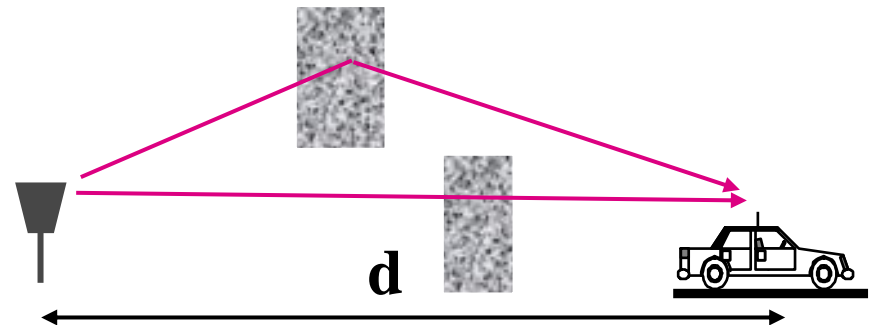
$$P_r = P_t K \left[ \frac{d_0}{d} \right]^\gamma, \quad 2 \leq \gamma \leq 8$$

- Shadowing

- dB value is Gaussian
- Find path loss exponent and shadow STD by curve fitting

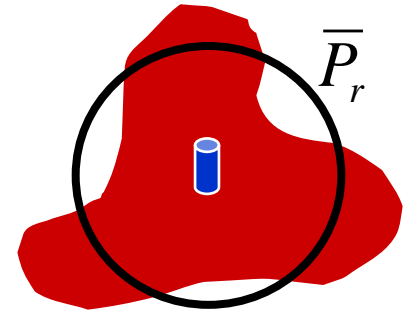
- Multipath

- Ray tracing
- Statistical model

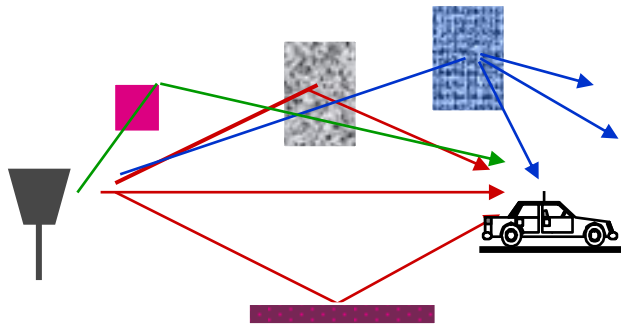


# Outage Probability and Cell Coverage Area

- Path loss: circular cells
- Path loss+shadowing: amoeba cells
  - Tradeoff between coverage and interference
- Outage probability
  - Probability received power below given minimum
- Cell coverage area
  - % of cell locations at desired power
  - Increases as shadowing variance decreases
  - Large % indicates interference to other cells



# Statistical Multipath Model



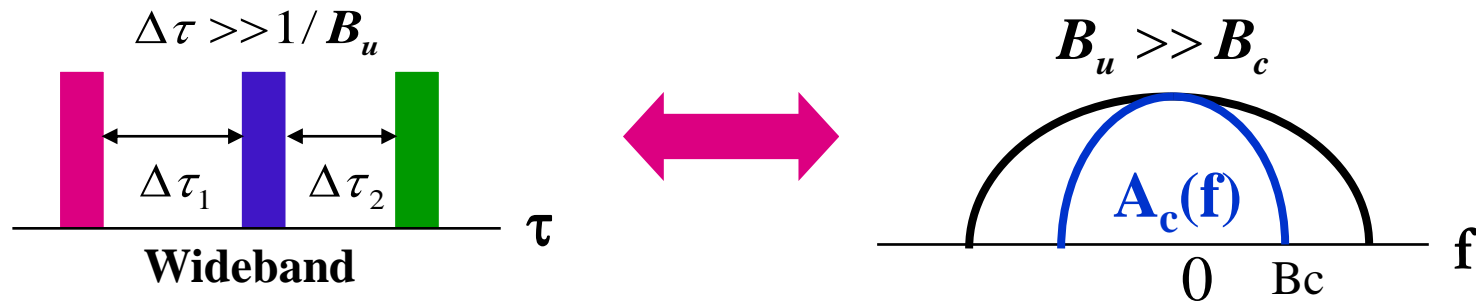
- Random # of multipath components, each with varying amplitude, phase, doppler, and delay
- Leads to time-varying channel impulse response

$$\mathbf{c}(\tau, t) = \sum_{n=1}^N \alpha_n(t) e^{-j\varphi_n(t)} \delta(\tau - \tau_n(t))$$

- Narrowband channel
  - No signal distortion, just a complex amplitude gain
  - Signal amplitude varies randomly (Rayleigh, Ricean, Nakagami).
  - 2<sup>nd</sup> order statistics (Bessel function), Average fade duration
  - Can also model amplitude variations via a Markov model

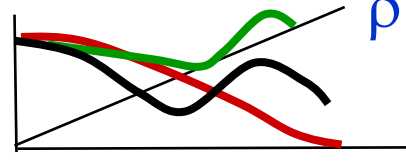
# Wideband Channels

- Individual multipath components resolvable
- True when time difference between components exceeds signal bandwidth



- Scattering function

$$s(\tau, \rho) = \mathcal{F}_{\Delta t}[A_c(\tau, \Delta t)]$$



Doppler Power Spectrum

Delay Power Spectrum

- Yields delay spread/coherence BW ( $\sigma_\tau \sim 1/B_c$ )
- Yields Doppler spread/coherence time ( $B_d \sim 1/T_c$ )

# Capacity of Flat Fading Channels

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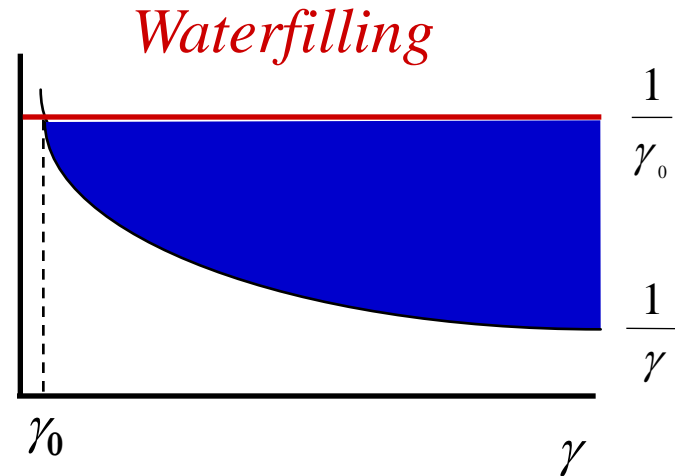
- Three cases
  - Fading statistics known
  - Fade value known at receiver
  - Fade value known at receiver and transmitter
- Optimal Adaptation with TX and RX CSI
  - Vary rate and power relative to channel
  - Goal is to optimize ergodic capacity

$$C = \max_{P(\gamma) : E[P(\gamma)] = \bar{P}} \int_0^{\infty} B \log_2 \left( 1 + \frac{\gamma P(\gamma)}{\bar{P}} \right) p(\gamma) d\gamma$$

# Optimal Adaptive Scheme

- Power Adaptation

$$\frac{P(\gamma)}{\bar{P}} = \begin{cases} \frac{1}{\gamma_0} - \frac{1}{\gamma} & \gamma \geq \gamma_0 \\ 0 & \text{else} \end{cases}$$



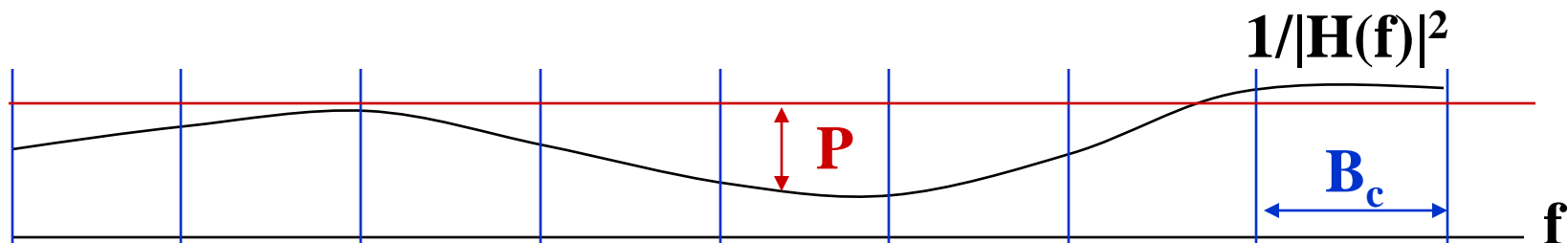
- Capacity

$$\frac{R}{B} = \int_{\gamma_0}^{\infty} \log_2 \left( \frac{\gamma}{\gamma_0} \right) p(\gamma) d\gamma.$$

- Alternatively can use channel inversion (poor performance) or truncated channel inversion

# Frequency Selective Fading Channels

- For time-invariant channels, capacity achieved by water-filling in frequency
- Capacity of time-varying channel unknown
- Approximate by dividing into subbands
  - Each subband has width  $B_c$  (like MCM).
  - Independent fading in each subband
  - Capacity is the sum of subband capacities



# Modulation Considerations

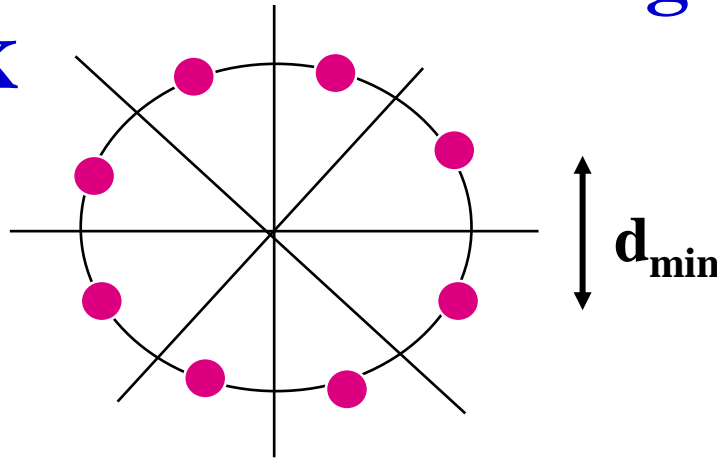
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- Want high rates, high spectral efficiency, high power efficiency, robust to channel, cheap.
- Linear Modulation (MPAM, MPSK, MQAM)
  - Information encoded in amplitude/phase
  - More spectrally efficient than nonlinear
  - Easier to adapt.
  - Issues: differential encoding, pulse shaping, bit mapping.
- Nonlinear modulation (FSK)
  - Information encoded in frequency
  - More robust to channel and amplifier nonlinearities

# Linear Modulation in AWGN

- ML detection induces decision regions

- Example: 8PSK



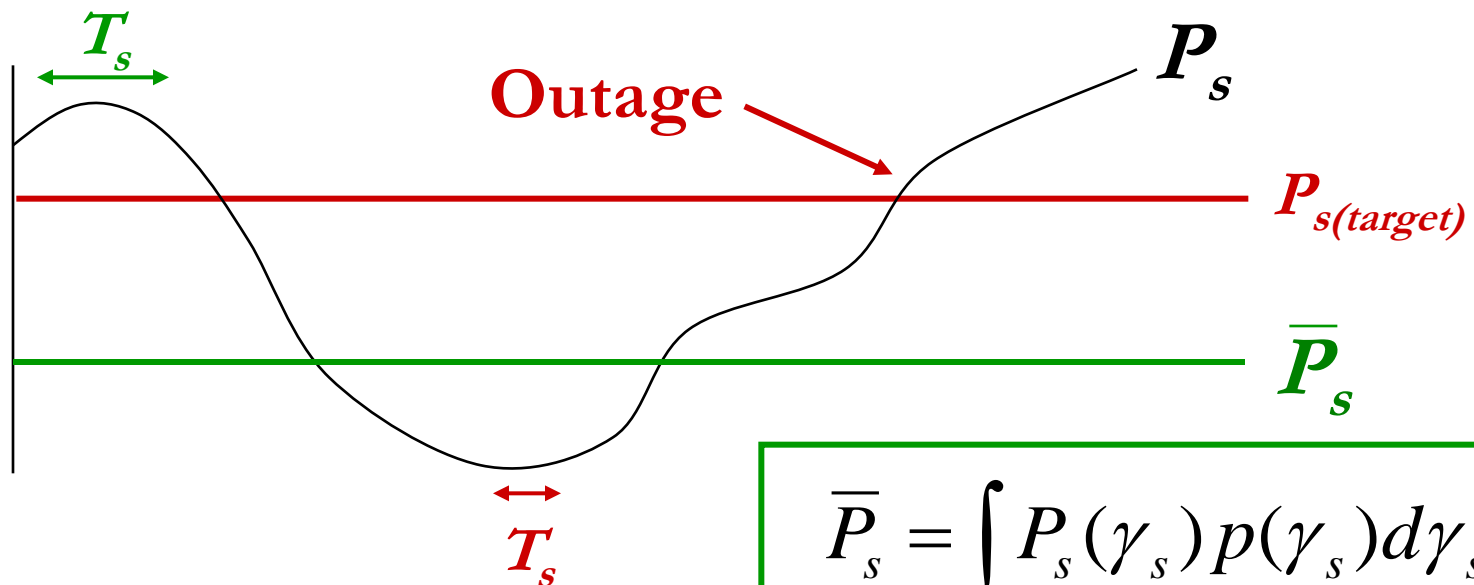
- $P_s$  depends on

- # of nearest neighbors
- Minimum distance  $d_{\min}$  (depends on  $\gamma_s$ )
- Approximate expression

$$P_s \approx \alpha_M Q\left(\sqrt{\beta_M \gamma_s}\right)$$

# Linear Modulation in Fading

- In fading  $\gamma_s$  and therefore  $P_s$  random
- Metrics: **outage**, **average**  $P_s$ , combined outage and average.



# Moment Generating Function Approach

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- Simplifies average  $P_s$  calculation
- Uses alternate Q function representation
- $\bar{P}_s$  reduces to MGF of  $\gamma_s$  distribution
- Closed form or simple numerical calculation for general fading distributions
- Fading greatly increases average  $P_s$ .

# Doppler Effects

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- High doppler causes channel phase to decorrelate between symbols
- Leads to an irreducible error floor for differential modulation
  - Increasing power does not reduce error
- Error floor depends on  $B_d T_s$

# ISI Effects

- Delay spread exceeding a symbol time causes ISI (self interference).



- ISI leads to irreducible error floor
  - Increasing signal power increases ISI power
- ISI requires that  $T_s \gg T_m$  ( $R_s \ll B_c$ )

# Diversity

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- Send bits over independent fading paths
  - Combine paths to mitigate fading effects.
- Independent fading paths
  - Space, time, frequency, polarization diversity.
- Combining techniques
  - Selection combining (SC)
  - Equal gain combining (EGC)
  - Maximal ratio combining (MRC)
- Can have diversity at TX or RX
  - In TX diversity, weights constrained by TX power

# Selection Combining

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- Selects the path with the highest gain
- Combiner SNR is the maximum of the branch SNRs.
- CDF easy to obtain, pdf found by differentiating.
- Diminishing returns with number of antennas.
- Can get up to about 20 dB of gain.

# MRC and its Performance

- With MRC,  $\gamma_{\Sigma} = \sum \gamma_i$  for branch SNRs  $\gamma_i$ 
  - Optimal technique to maximize output SNR
  - Yields 20-40 dB performance gains
  - Distribution of  $\gamma_{\Sigma}$  hard to obtain
- Standard average BER calculation

$$\bar{P}_b = \int P_b(\gamma_{\Sigma}) p(\gamma_{\Sigma}) d\gamma_{\Sigma} = \int \int \dots \int P_b(\gamma_{\Sigma}) p(\gamma_1) * p(\gamma_2) * \dots * p(\gamma_M) d\gamma_1 d\gamma_2 \dots d\gamma_M$$

- Hard to obtain in closed form
  - Integral often diverges
- MGF Approach

$$\bar{P}_b = \frac{1}{\pi} \int_0^{.5\pi} \prod_{i=1}^M \mathcal{M}_i \left[ \frac{-g}{\sin^2 \varphi}; \gamma_i \right] d\varphi$$

# EGC and Transmit Diversity

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- EGC simpler than MRC
  - Harder to analyze
  - Performance about 1 dB worse than MRC
- Transmit diversity
  - With channel knowledge, similar to receiver diversity, same array/diversity gain
  - Without channel knowledge, can obtain diversity gain through Alamouti scheme: works over 2 consecutive symbols